


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1 FOREWORD, SCOPE AND PURPOSE

This document is submitted in compliance with the requirements of NASA contract 9-17877. It constitutes the Task Report for Task 2 of the related Statement of Work, as per DRL: T-2067, DRD: SE 1111T.

The focus of this document is on the evaluation of the whole of the experiments performable in a variable gravity environment, and the related compatible/beneficial residual accelerations, both for pure and applied research in the fields of Fluid, Materials and Life Sciences, so as to assess the relevance of a variable g-level laboratory.

The purpose of the present document is twofold:

- to assess which experiments may take advantage of the controlled, variable acceleration levels provided by a Tethered Variable Gravity Laboratory,
- to establish the requirements applicable to such a Laboratory in terms of:
 - magnitude,
 - direction and
 - frequencyof the intentional and residual acceleration levels.

The authors are indebted to Dr.V.Guarnieri for his contributions to the sections of the present report dedicated to life sciences.

2 STATEMENT OF THE PROBLEM AND STUDY APPROACH

The approach to the analysis described in this document is better understood if a synthetic picture of the experimental background is given.

Since the Apollo and Skylab era as many as 500 experiments in Material and Life Sciences fields have been performed in absence of gravity, both on board orbiting vehicles and during parabolic trajectories.

Some facts which have emerged from these experimental activities and from the analysis of their outputs prompt the considerations illustrated below.

Even if the condition of reduced residual acceleration is essential to the experimental purposes, accurate measurements of this condition close to the experimental volume were often neglected, particularly in the past.

After an initial period characterised by demonstration purposes, experimental activities were prematurely turned towards material production, which often did not produce the anticipated results due to the onset of unforeseen physical effects masked on ground by stronger ones.

Although in the recent past a trend inversion has appeared and the need to understand the basics of microgravity experiments has been acknowledged, pure and applied scientists have nowadays more results than firm qualitative or quantitative explanations.

In particular, what is missing is the measurement of the acceleration history (g-profile) of the experiments, to be compared with the theoretical predictions of the influence of the residual acceleration vector, not only as a steady field, but also as a function of frequency.

On the other side theoretical analyses, too, are not always available or are sometimes limited to particular cases, hampering the search for widely applicable experiment-theory correlations.

The activity covered in this report moves from such a situation and ultimately aims at assessing the worthiness of a variable acceleration laboratory for science/production purposes.

In order to systematically and effectively analyse the aspects related to such a goal within the study frame, an approach based on experiment "building blocks" was selected.

Indeed, the number of basic physical and chemical phenomena involved in micro-g experiments is limited compared to that of the possible experiments and processes themselves. The starting point of the activity, therefore, was found in the review of the available literature in Fluid Statics and Dynamics, in Thermodynamics and Physical Chemistry, as they face directly the analysis of the fundamentals of such basic phenomena as convection, diffusion, interface stability a.s.o., which provide the key to the understanding of applied science experiments and production oriented tests.

The review was then to be completed in the Materials Science fields, (Crystal Growth, Metal and Alloy Solidification, Glasses, ...), by looking for the influence of the previously studied elementary effects on each phase of the considered processes.

Parallel to the mentioned review, mathematical analyses of the relevant physical observables dependance on the g-level were planned being looked after.

These are usually, but not always, performed by dimensional analyses which correlate the physical variables by grouping them in dimensionless numbers, and allow to take into account widely extended experimental configurations relevant to the same phenomenon.

In case that possible uncovered areas had been highlighted, a few experts, when appropriate, were to be contacted in order to ascertain whether further unpublished analyses exist.

Preliminary results were - according to the original approach - to be eventually derived in terms of variable g relevance for each experiment class and process or technique by means of the mentioned mathematical analyses and, when appropriate and possible within funding and time constraints, cross-checked and supplemented by experts/scientists advice.

The relevant experiments were finally to be listed and their reduced gravity profiles provided as function of time.

A different approach was chosen for Life Science experiments, whose analysis is usually not pursued by means of mathematical methods due to the intrinsic nature and complexity of the biological phenomena.

G-influence and g-variation relevance to the experiments were to be evaluated directly by literature review and

expert consultation via a phenomenological but not mathematical analysis.

As a matter of fact, the above described approach was partly changed during the course of the activity, enhancing the importance of the direct consultation of the scientists versus the theoretical literature elaboration in order to assess variable gravity worthiness for the experimental areas in microgravity.

Reasons for this approach adjustment are detailedly explained in the following (see chapter 3.3). Here it is sufficient to point out that the presence of several uncertainty factors, realised during the analysis of the theoretical studies, suggested this method to by-pass the obstacles.

Besides, the support coming from the existing theoretical analyses is usually oriented, when available, to the definition of the "optimal" conditions for each kind of experiment (that is: no gravity induced perturbations to the phenomena under study). On the contrary, it was often stated by the scientists that total gravity effect absence was not the only interesting condition, and sometimes a wide or even a full g-level range availability was declared useful.

In addition, the literature presently available and examined was very poor of suggestions concerning variable gravity uses in microgravitational sciences.

This led ultimately to the conviction that the wider and deeper a campaign of contacts with the involved investigators is, the more defined and complete panorama of possible scientific applications is obtained.

What was ascertained within the limits of the present study is reported in the following chapters.

The analytical part of the study is shown in chapter 3:

para 3.1 contains the results of the experimental activity review;
para 3.2 shows the gravity due effects per each of the previously analysed area;
para 3.3 depicts the estimated/suggested perspective of utilisation of the variable gravity laboratory.

Chapter 4 is the synthesis one, para 4.1 providing a synoptic view of the foreseen utilisation limits, while para 4.2 contains the basic requirements derived towards the hosting tethered platform.

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Chapter 5 is devoted to conclusive considerations and final recommendations for a possible future continuation of the investigation in the field of variable gravity applications.

3.0 EXPERIMENTAL AREAS ANALYSIS DETAIL

The experimental areas considered in this review are only those where both the reduced gravity aspect is directly essential to the experimental purpose (not merely the orbital position), and the possible applicability to a laboratory environment (close, limited in terms of physical and functional resources - volume, for instance).

Consequently, no pure Technology areas (e. g. robotics) are examined, as far as they are just support to microgravity related experimental areas.

In the same light, Space Sciences and Earth Observation purposes are not considered relevant to this study, as they are concerned with the orbital position, not with the weightlessness aspect.

Full attention is given, on the contrary, to Materials and Life Science disciplines.

3.1 REVIEW OF PERFORMED OR PERFORMABLE EXPERIMENTS

In the following, materials and life sciences experiment areas will be dealt with in two separate, dedicated chapters.

Material science area includes all the experiment classes where materials are involved and where physical and/or chemical phenomena play the key role, without biological phenomena activation. Thus, protein crystal growth and biological materials separation techniques are included here.

On the contrary, life sciences area includes all the experiment classes where effective biological or biochemical phenomena are present.

3.1.1 Material Sciences Experiments

Under this general heading both material production experiments, such as crystal growth, metal and composite solidification from a liquid phase, applied chemistry and so on, and pure science experiments in physics and physical chemistry are included.

Actually, due to the partial overlapping of the objectives of the two fields (pure science or production) a distinction based on the processed sample state of aggregation might be more effective. Experiment branching into solidification and fluid science classes looks attractive under this respect.

The main areas of investigation can, however, be defined as follows. In the pure science domain one can identify the following two main areas:

- fluid mechanics, where mainly fluid statics and dynamics are involved, even in the presence of thermal fields,
- thermodynamics/physical chemistry where, although mechanical effects on the fluid phases are present, the emphasis is on the phenomena related to thermodynamics, with or without the presence of chemical reactions.

Obviously, the two mentioned areas show some overlapping in certain experimental domains.

As far as applied sciences are considered, most experiments are focused on material production, usually via solidification from a liquid phase. The following broad classification into three main areas is suggested:

- crystal growth, aimed at producing inorganic as well as organic (proteins) materials under crystalline form, mainly from a melt or a liquid solution, sometimes by deposition or transport from a vapour;
- metallurgy, where metallic materials, pure or reinforced with additional components, are looked for; metallic (as well as non metallic) glasses are included in this area;
- bioseparation, which includes all separation processes on biological or farmaceutical compounds.

In the following sections, the experiments belonging to each one of the above identified areas are examined by class, in the same order as they appear above.

- Fluid mechanics: statics

The distinction between the experimental areas named fluid statics and fluid dynamics is not a clearcut one: fluid column rotation, for instance, is assigned to fluid statics even if a (rigid) motion is present in the search for equilibrium configurations and their limits.

In general, fluid statics deals with the investigation of equilibrium configurations of liquid masses (with completely or partially free surface) under the competitive effects of surface/interface tension and gravity. In addition to gravity, other bulk forces can be applied, such as centrifugal fields or electrical fields.

Subjects of interest are:

- shape and stability of masses of pure liquids
- contact angles of the liquid(s) with their boundary solid walls, also when approaching a critical point (critical wetting)
- interface behaviour of different contiguous liquid masses
- capillary phenomena, such as meniscus level and shape in capillary tubes.

As illustrated herebelow, microgravity experiments have so far been mainly concerned with the problem of stability and shape of liquid bridges when surface tension becomes predominant over gravity.

Under such conditions, the extension and the shape limits and stability of steady (unrotated) liquid bridges between two boundary plates (with equal or different radii) have been investigated.

This has usually been done by increasing plate separation at constant fluid volume or by depleting the column at constant separation.

A few other experiments have been performed on different, non-axisymmetric liquid portions, such as a liquid lens stretching across the space enclosed by three solid spheres, or an annular ring of water around a cylindrical support, showing a nodoidal instability.

The behaviour of rotating liquid bridges has been subject of attention in a number of experiments. These were aimed at defining symmetry stability limits and decay modes (amphora and jump rope or C-mode instabilities) for columns with different aspect ratios. Bridge rupture limits were also investigated.

The rotational stability of individual drops was also investigated, by means of an acoustic levitation chamber, and it turned out that surface deformation increased with increasing rotation speed.

The oscillatory behaviour of tethered drops and liquid bridges has also been investigated in order to obtain an experimental map of the frequency response spectrum as a function of the bridge aspect ratio.

The presence of an electrically charged surface was observed to produce deformation of a tethered liquid drop from spherical to conical shape.

Additional experiments have already been proposed for future investigations of critical wetting and critical adsorption phenomena which are, however, common to the area of near-critical phenomena. Enhancement of the experimental activity on the effect of the electrostatic charge on fluid interface behaviour is also being suggested.

- Fluid mechanics: dynamics

Generally speaking, fluid dynamics includes those experiments where a motion develops or is set up within the volume of the fluid.

Most experiments performed to date fall in the pure science field, while much fewer were application oriented ones such as heat pipe, fluid sloshing in tanks and so on.

A large share of experimental activities was devoted to the study of thermocapillary (Marangoni) flow onset, development and establishment. Typically, a temperature gradient is imposed on a liquid column by heating up one of the two end plates which sustain its ends. Tracers or bubbles are then used to detect Marangoni thermal convection.

They monitor the stability and the transition to oscillatory behaviour of Marangoni convective motions, which originate in the liquid layers close to the column free (lateral) surface when a temperature gradient induces a surface tension gradient. Boat configurations are also used.

Likewise, a chemical concentration gradient generates a surface tension gradient which, in turn, sets up the so-called Marangoni solutal convection. This can be detected under microgravity conditions and, indeed, it

is studied. The effects of coupled thermal and solutal gradients is also subject to measurements.

Additional stimulations, such as electric fields, were also applied during the experiments to observe the sample response. Internal flow fields (forced oscillations and so on) in experiments whose main goal was fluid statics were also recorded and studied.

Similarly, bulk flows due to capillarity were also studied both in cylindrical tanks (with additional mechanical perturbations) and in other variously shaped containers.

Surface motions (waves), where capillarity plays the prevailing role, were taken into account, too.

Not only monophasic, but also bi- and poly-phase fluids (mixtures) are considered as experimental media.

The boiling of liquids in the absence of gravity was also studied from an experimental viewpoint and fundamental aspects of heat and mass transfer and of nucleation were recorded.

During the Spacelab-1 flight, the kinetics of a silicone oil drop spreading was investigated. Mixing and demixing of different transparent fluids with a miscibility gap was also observed.

Several experiments were also devoted to the analysis of fluid-dynamical effects relevant to other experiment areas, e.g. crystal growth from solution, (for instance: flow field interaction with and stability of the solidification front), electrophoresis and critical point phenomena; they are, however, dealt with in the relevant sections.

- Thermodynamics/physical chemistry

Even though the number of experiments performed in this area is not so high as in other ones, its potential interest is considered rather relevant.

One can subdivide it according to the presence or the absence of chemical reactions into branches mainly concerning thermodynamical matters, such as:

- thermodynamical properties, both of equilibrium state and of irreversible processes
- transport properties of high temperature liquids, such as diffusion coefficients
- critical point phenomena
- phase boundary and adsorption phenomena, and branches where chemical reactions are involved in the process:
- combustion
- electrochemistry
- chemical kinetics and physico-chemical processes
- relaxation phenomena.

The various branches are individually examined in the following.

- Thermodynamics/physical chemistry: thermodynamics

Thermodynamics (thermodynamical properties, critical point phenomena, etc.) show the following areas of interest:

- measurements of thermodynamic functions of corrosive substances
 - measurements of pressure, temperature and specific volume near the critical point of single fluids
 - observation of the distribution of particles and/or bubbles in melts
 - equilibrium distribution in a fluid at the critical point
 - separation of binary mixtures and spinodal decomposition
 - boiling phenomena
- and so forth.

Up to now, few experiments have been performed in space to investigate such interface phenomena as wetting and adsorption near a critical point. These would help validating theories concerning the scaling of correlation lengths, the interface thickness, the surface tension, the wetting transition effects and contacts angles and the scaling of adsorption.

Phase transitions and thermodynamic properties near the critical point are, on the contrary, the subject of a

greater number of experiments, both on Spacelab missions and in sounding rocket (TEXUS) campaigns.

Experiments have been carried out to measure the isochoric specific heat at constant volume while approaching a liquid-to-vapour transition. Other experiments were concerned with separation at and near critical points.

Transport phenomena are also of great interest because transport coefficients can be precisely measured only in space since, on ground, thermal gradients lead to convection. In particular, the following phenomena have been studied:

- mass transport by diffusion, both self diffusion of different isotopes of the same metal (for instance zinc or tin) and diffusion of different substances into each other (e.g. two metals such as gold and lead or two glass melts)
 - mass transport due to Soret effect, that is the segregation of different mass species resulting from a temperature gradient. This experiment was performed on a mixture of cobalt and tin and on a mixture of silver iodide and of a potassium iodide.
- Thermodynamics/physical chemistry: **physical chemistry**

Few topics in this field have been subjected to direct verification by means of space experiments. They are examined in the following.

Chemical reactions and processes are, in general, affected by gravity: this is true for heterogeneous catalytic processes, fluidized beds, separation, solvent extraction, distribution, adsorption, evaporation, structure of interfaces, aerosol chemistry and so on.

Potential interest in gaining further insight in these processes is motivated by their use in terrestrial applications. So far this area is, however, uncovered in space programs.

Experiments are also being called for to evaluate the influence of gravity on chemical pattern formation by oscillatory chemical reactions.

Chemical instabilities arising in systems far from thermodynamic equilibrium are presently matter of theoretical investigations, which may be validated by future experiments in the (gravity-driven) convection-free microgravity environment.

Relaxation phenomena induced by the absorption of ultrasonic waves in molten salts are pointed out as a good subject for experiments in microgravity. Indeed, on the ground, convective phenomena hamper the correct determination of the absorption coefficients, which are derived from measurements of the density variations induced by the acoustic wave.

Applied electrochemistry is also suggested as an interesting field for space-based experiments. Such effects as electrocapillarity, electromigration and the processes in the electrolyte-to-electrode diffusive layer are considered. Electrolysis has, in fact, already been investigated in some experiments on the dispersion electrolysis and the subsequent deposition on the cathode and on the electrolytical generation of hydrogen on a metallic cathode.

Combustion is the area with the highest experimental activity. This may be due to the high interest in the definition of safety conditions for pressurized, manned flight environment. Indeed, during combustion chemical reactions turn the reagents into products and large amounts of heat.

Transport processes play there a major role, both in gaseous fuel transfer (and mixing, when unpremixed flames are involved) to the combustion area and in exhaust gas release. When non-gaseous fuels are used, liquid/solid fuel vaporization/sublimation phenomena are also involved.

Besides mass transport, heat transport is involved in the process for reagent heating, vaporization, sublimation, exhaust product expulsion and so on.

The theories which describe these coupled phenomena are difficult to test on ground due to the convective mass transport set up by the combustion-generated temperature gradients. In orbit, on the contrary, convective contributions can be separated and theories can, thus, be validated.

The simulation of purely diffusive flame propagation in dust-air mixtures is also extremely interesting. Liquid droplet combustion experiments have been performed in drop towers and, recently, in parabolic flights, for theory validation. Experiment replay in orbit is planned for the future.

Another interesting field is represented by flame spreading along solid surfaces. Even in purely diffusive

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conditions some momentum is generated during fuel
pyrolysis or vaporization.

Investigations began in parabolic flights by means of an
aircraft-mounted combustion chamber. The extension of
these activities to spacecraft environment is expected
in the next future.

- Crystal growth

The discipline of crystal growth is concerned with the production of several crystalline materials starting from or passing through a fluid phase. On orbit crystal production is interesting because crystal purity, dimensions and structural characteristics can be greatly improved.

In other words, purer and larger crystals can be obtained without dislocations and voids, with virtually perfect reticular structure and with no strain fields. The produced materials are mainly used in electronics (semiconductors), in laser optics and in radiation detectors.

Many processes and techniques are employed on ground, but not all of them are applied or applicable in microgravity. They are usually grouped, according to the nature of the fluid phase from which the crystal is grown, in the following classes:

- crystal growth from melt
- crystal growth from solution, including protein crystallisation
- crystal growth from vapour.

- Crystal growth: crystal growth from melt

This method allows the crystal to be obtained by solidification from a fluid phase - the melt - which is the same substance of the crystal. However, when a doped material is solidified, a segregation process takes place, due to the fact that the solid phase allowed concentration of the dopant is different from the liquid phase one, giving origin to a solute (dopant) spacial concentration field in the liquid portion and to a variable distribution of dopant in the solid one. Similar phenomena occur in mixed crystals.

This technique usually requires high temperatures, and is applied to the production of solid state electronics, such as doped semiconductors for integrated circuits, laser host lattices (oxides), scintillators (halides).

A variety of techniques is employed on ground, such as, for instance:

- Czochralsky technique, that is the extraction of a crystal seed from the melt contained in a crucible, under a temperature gradient allowing the solid to grow on the seed, which is rotated to avoid dishomogeneities
- Bridgman technique, or directional solidification, in which a vertical cylinder or a horizontal open boat

filled with the fused charge material is submitted to a thermal gradient, which is in relative motion respect to the sample permitting to the solidification front to proceed

- Zone Melting technique, similar to the Bridgman technique, where only a small section of a vertical or horizontal rodlike ingot is melted; the zone passage from the beginning to the end of the rod can be repeated
- Floating Zone technique, a variation of the previous one, where the ingot container is not present and containment is assured by the surface tension of the liquid portion.

A large number of space based experiments on growth from melt have been performed to date, on Skylab, ASTP, Salyut, Spacelab, Spacelab D-1, Texas. Most of them were concerned with semiconductors.

Thus, the techniques are essentially:

- directional solidification of melts in cylindrical quartz ampoules, using a shifting thermal gradient or a movable sample with a fixed gradient
- floating zone crystallisation performed by means of mirror furnaces focusing radiation on a movable bar-shaped sample.

Future activities are suggested to extend the range of processed materials, including those with high melting temperature which are required in electronics. Progress is expected also in processing techniques, with a transition towards containerless or quasi wall-free methods. Some aspects are, however, still to be clarified, for instance drop seeding and vapour pressure control.

- Crystal growth: crystal growth from solution

In this case the crystal is obtained by the gradual incorporation on a "seed" of a solute which is transported through the solution up to the surface of the growing crystal.

The presence of thermal and solutal fields, needed or caused by the growth process, may give rise to gravity- or surface-tension-driven convection. This usually disturbs pure diffusion because it may increase crystal inhomogeneities and striations.

Two main process areas are identified depending on the temperature at which the crystal is grown, namely high and low temperature processes.

High temperature processes may concern both metallic and non-metallic solutions. No space-based experiments have been performed to date on the latter (the so-called flux growth method) which is, however, referred to as potentially beneficial.

In flux growth, molten salts are used as solvents and the temperature, though high, is lower than in the case of melt growth. This helps reducing the generation of dislocations in the crystal.

Magnetic materials are produced this way; they are used in communication systems (bubble domains, bandpass filters and so on) and in laser and non linear optics.

Microgravity may be beneficial to this technique, particularly for closed systems using low vapour pressure solvents. In space, the forced convection needed to provide stirring and avoid gravity-driven convection irregularities may be substituted with purely diffusive convection.

Growth from metallic solutions applies to III-V and II-VI semiconductors for optoelectronic devices and integrated circuits and for infrared-transparent materials and electro-optic modulators respectively.

The Bridgman and the traveling heater techniques were successfully applied in the Spacelab-1 and D-1 missions. Reduction of dopant striations was the major benefit of the purely diffusive conditions achieved in space.

Low temperature methods are more practical than high temperature ones and do not give rise to after-growth cooling problems. Different techniques are adopted depending on the solubility of the material to be crystallized. At any rate, the number of space-based experiments performed to date with this method is rather small.

Low solubility materials (less than 1 g/l) are processed on ground by means of the gel growth technique. In space, the crystals are obtained by counter-diffusion of pure reactant solutions within a buffer solution where nucleation is initiated and growth proceeds. Gel inclusions and convection-induced damages are avoided in space.

High solubility materials (more than 1 g/l) have been the subject of few space-based experiments only. Crystals are obtained by precipitation on a "seed" or by nucleation.

Growth phenonema, however, are not fully mastered. Different habits have, for instance, been observed in crystals grown in space and on ground under the same conditions (other than microgravity). The sensitivity to nucleating crystal drifting seems to be lower than calculated.

Nevertheless, the onset of purely diffusive nutrient transport to the growing crystal is considered beneficial to the perfection of the final product.

Protein crystal growth is related to the above-reviewed low temperature, low solubility growth techniques. It focuses on producing well defined materials, namely protein crystals of size and purity sufficient to allow X-ray analysis and internal structure definition.

European and American teams have performed several space-based experiments and have obtained valuable results using different techniques.

The Europeans have exploited counter-diffusion of a protein solution and of a salt solution in a buffer solution; the second was used to induce protein precipitation. Owing to the absence of gravity, density-driven turbulent convection was avoided and pure diffusion brought to good results.

Purely diffusive conditions were also achieved in the American experiment. This achieved microcrystallization by means of the hanging drop and of the microdialysis cell methods, both based on principles similar to those of the European technique.

- Crystal growth: crystal growth from vapour

Nutrient transport to the growth interface is achieved in this method by turning the substance to be crystallized, whose vapour pressure should be high enough at the processing temperature, into a vapour.

The source material is heated up and made to sublime into a vapour; a temperature gradient is then set up so that the growing crystal is in such thermodynamic conditions as to receive and incorporate the nutrient vapour. This technique is called Physical Vapour Transport (PVT).

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PVT method is substituted by either Chemical Vapour Transport (CVT) or Deposition (CVD) processes whenever a crystal of a non-volatile substance is desired. A chemical reaction with a transport agent or the deposition from gaseous reactants is then required, for CVT and CVD respectively, to realise the cristallisation from the vapour phase.

Vapour growth techniques are of great importance and of widespread use because they allow to obtain crystals with considerably lower defect densities than other (higher temperature) methods. They also allow treating materials which decompose before melting or which react with the crucible or with the solution.

Very few experiments have been performed in space up to now. They were aimed at growing mercury iodide ($\alpha\text{-HgI}_2$, important for gamma ray scintillators) and germanium crystals mainly. Good structural quality and electronic properties have been obtained.

Future applications foresee extending the temperature range of the processes and indicate precise measurements of diffusion coefficients as a major objective.

- Metallurgy

Metallurgy deals with the production of metals and metallic alloys by solidification from the liquid state. This can result in crystalline or glassy metals and alloys.

Metallurgy is largely represented in space activities: the focus, however, is not on large scale material production but rather on the understanding which can be gained about the physics governing solidification.

Space experiment are also aimed at improving the knowledge about the way technological processes such as brazing or welding behave in space.

Metallurgy processes can be broadly classified as follows, depending on the final products of solidification:

- pure metals and alloys with no miscibility gap in the liquid state (complete miscibility)
- alloys with miscibility gap in the liquid state
- composites
- metallic and non-metallic glasses.

- Metallurgy: metals and alloys

As far as pure metals and completely miscible alloys are concerned, space experiment dealt mainly with casting and directional solidification. Some successful "technology" experiments have also been performed to check the possibility to perform welding in space.

The experiments were aimed at studying the physics of solidification in an environment where purely diffusive effects can be separated from gravity-driven convection phenomena linked to liquid-to-solid interface advancement.

Experiments concerned with casting were first performed during the SPAR campaign. They aimed at observing bulk solidification characteristics and made use of metallic systems and model (transparent) matrices.

Observed low-gravity effects consisted in the formation of larger grains and in better isotropy than in ordinary (or higher) gravity.

Directional solidification experiments considered solidification front macro-segregation, morphological stability and dendritic growth.

Temperature and solutal gradients near the solidification front generate convective flows which, in turn, influence the undercooling, nucleation and growth phenomena ruling the above-quoted aspects.

Space-based experiments have been aimed at highlighting the different contributions affecting the above mentioned aspects. They were usually in good agreement with theoretical predictions based on pure diffusion assumptions.

Metallic alloys with a miscibility gap (while in the liquid phase) were also worked on in space, due to the possibility to avoid sedimentation and buoyancy effects.

This is particularly relevant for liquids with different densities, which separate from each other when the miscibility gap part of the phase diagram is reached. Thus, in principle the final solid is not perturbed by gravity-driven additional effects.

The following areas of interest were tested with some care in order to provide experimental support to the related theories:

- nucleation, i.e. the formation of second phase liquid droplets into the first phase and undercooling relevance
- growth of nucleated drops: size distribution and migration were analysed.

No experiments have been performed to date on droplet coalescence and coagulation; this topic is, indeed, proposed for future space-based activities.

- Metallurgy: composites

Composite materials (composites) are characterized by a microscopically heterogeneous mix of two solid phases which give rise to a macroscopically homogeneous structure with physical properties different from those of the constituents.

The only interesting method for composite production in space is melt processing. This is true both for in situ, and for artificial composites.

The reinforcing component of the former is obtained from a homogeneous liquid alloy whose solidification segregates a minority phase which acts as the reinforcing structure within the surrounding matrix.

The latter composites are reinforced by elements introduced from outside into the matrix. The subsequent

fusion and solidification are only aimed at providing the correct reinforcing component distribution into, and bonding to, the heterogeneous matrix in the final form.

In situ composites can be obtained by solidification of eutectic alloys: the resulting reinforcing structure can be lamellar, rod-like or irregular.

Since Skylab, and up to the German Spacelab D-1, several experiments have been performed in space. They have shown that space-processed samples usually display a lower fault density, longer fibres and a different, usually smaller, fibre density.

Solidification of peritectic systems was also considered, but fewer experiments have been performed in this area. The prepared composite, a MnBi alloy, showed better magnetic properties due to the absence of sedimentation.

Finally, monotectic systems can be directionally solidified in space. Fibrous or globular or non-regular structures are obtained in this case depending on the metallic system. No space experiment, however, was directly aimed at producing exactly monotectic structures.

Artificial composites are obtained by adding fibres or particles to improve the mechanical properties of the matrix material. Otherwise, a gaseous phase can be added to the matrix to reduce its density.

Many experiments have been performed in the former area to verify theoretical predictions, while fewer were carried out in the latter group.

Their results are not fully conclusive. Indeed, they show that, even under reduced gravity, fibre or bubble uniform distribution, correct separation and non-agglomeration are not always achieved due to other, g-independent phenomena such as matrix-particle/bubble wetting.

- Metallurgy: glasses

Glassy states can be obtained both for metallic and for non-metallic substances. The interest in producing them in microgravity is related to the greater purity achievable for known materials and to the possibility to get new ones whose production is impaired by gravity.

Glasses are mostly produced by cooling the glass melt below the melting point. This has to be done fast enough

to prevent atom or molecule ordering in crystalline lattices.

Contributions to solid elements formation into the bulk come from intrinsic (homogeneous) nucleation and from the effect of contaminants at the boundaries (heterogeneous nucleation).

Heterogeneous nucleation suppression by containerless processing allows to reduce the critical cooling rate; this is beneficial, particularly to obtain bulk metallic glasses.

Experiments aimed at preparing metallic glasses have been performed by means of drop towers. One attempt to do the same on orbit ended up in a failure. Nevertheless, several experiments are now in preparation for containerless melting facilities.

Several non-metallic samples have, on the contrary, been obtained in space since the early days of microgravity research. The experiments were aimed at glass formation and at investigating kinetic processes, in particular the determination of diffusion coefficients for the liquid phase. Better homogeneity and lower undercooling were the most important results of these experiments.

- Bioseparation

This area of space experimentation is aimed at improving the separation efficiency of biological materials such as cells and proteins and at enhancing the purity of their fractions.

Electrophoresis was adopted since the beginning of space activities but, more recently, phase partitioning was also added as a separation technique.

Electrophoresis consists of the separation of different substances by means of a static electric field in a separation cell. Several configurations are possible on ground.

During the Apollo missions some preliminary experiments were performed. Analytical electrophoresis was subsequently tested as part of the Apollo-Soyuz Test Project (ASTP).

Continuous flow and isoelectric focusing electrophoresis were eventually selected as the preferred methods for space-based experiments.

In continuous flow electrophoresis experiments, the sample is (continuously) injected into a separation chamber filled with a liquid buffer. The applied electric field is normal to the injected flow.

The products are separated according to their charge/mass ratio and are collected on the side opposite to the injection nozzle.

The main problems are the deformation and the loss of resolution and of purity of the streams after separation. They are due to friction with the buffer liquid, to electro-osmosis and to the buoyancy caused by the temperature gradient across the chamber.

Several experiments have been performed to date, after the ASTP first attempts, by means of the Continuous Flow Electrophoresis System (CFES, McDonnell Douglas).

Isoelectric focusing electrophoresis is used for proteins. Proteins are amphoteric compounds (containing both acidic and basic residues; only nucleic acids are not amphoteric): their net charge is determined by the pH of the medium they are in. In a solution with a pH above its isoelectric point (pI), a protein has a net negative charge, below its pI it is positive. By the application of a static electric field in a chamber

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where a pH gradient is maintained, a protein will focus where the local pH equals its pI. Hence a mix of different pI proteins can be separated.

This method was tested by means of the Recycling Isoelectric Focusing System (IFS) during the STS-11 mission.

Cell separation is normally achieved by phase partitioning, whereby two different polymers are mixed in aqueous solution to form a system of two immiscible solutions. A population with different cells is then added, shaken and allowed to settle.

Cell separation (partition) occurs between one of the phases and the interface. The phase containing the cells of interest is then extracted from the separation chamber. To achieve phase separation, electric fields have been investigated.

Gravity is essential in this process to achieve phase separation. Experiments show, however, that it disturbs cell separation during heavier phase droplet coalescence and precipitation. Indeed, it increases the droplet size, thus reducing the available separation surface.

Experimental work has been and is being performed to investigate phase partitioning in space.

3.1.2 Life science experiments

The present section deals with all the areas where biological phenomena are effectively involved. The following principal areas are outlined:

- Animal Physiology, including human physiology and space medicine (crew care and health maintenance)
- Plant Physiology, concerning plant growth in, and adaptation to, the space environment
- Cell Biology and Microbiology, dealing with behaviour, activity and genetic modifications of cells and bacteria
- Biotechnology, dealing with the activity of modified cells and microorganisms, for bioproduction purposes.

Unlike material science, where many experiments are nowadays specifically designed with the support of theoretical predictions, life science research is based on the comparison of "what happens in weightlessness" with analogous experiments on ground, looking for an experimental basis to future theoretical assessments.

Proven theories, models and quantitative predictions are far less common in life sciences. This is also due to the inherent difficulty in separating individual phenomena in living beings, with the possible exception of unicellular organisms.

The indication about how relevant microgravity variations are to living systems is, therefore, much rougher than for material science, especially for humans, animals and some plants.

The effect of microgravity on living organisms is, furthermore, somewhat cumulative (integrated over time, with initial adaptation), in that it often depends on the duration of exposure to weightlessness.

Thus, it is quite difficult to separate microgravity effects from phenomena due to artificial laboratory confinement, particularly for multicellular organisms.

The difficulty in associating microgravity to the biochemical cause of some macroscopic effects makes it very problematic to predict areas of life science research which would benefit from variable gravity.

Finally, experimental evidence was got that animals are generally little sensitive to how "deep" weightlessness is.

Thresholds are known to exist, but their position on the microgravity "axis" is affected by a large uncertainty, contrary to material science.

Self-generated acceleration levels (jumping monkeys, running guinea-pigs, working crew and so on) seem, however, to rule out human and animal (vertebrates) physiology, from the list of "most favoured users" of the variable gravity lab.

- Animal physiology

Since the beginning of the space activities, physiology studies have been aimed at assessing the influence of the prolonged absence of gravity on the human and animal body systems and organs.

A further major objective has also been to define and test measures and facilities capable to:

- maintain astronaut fitness against the negative effects of weightlessness and of prolonged permanence in constraining orbital vehicles
- assess the effectiveness and the possible deviation from normal ground behaviour of pharmacological aids as well as to define procedures and set up facilities for medicine and surgery in space.

Cardiovascular, respiratory, muscoskeletal, neurological, metabolic, endocrine, hematological systems have been investigated in man and animals, during several experiments, both in 0-g and on ground (weightlessness simulation in water or by particular manoeuvrings).

Animal models for microgravity experiments carried out so far have generally been little monkeys, rodents, amphibia, insects.

- Animal physiology: respiratory system

The studies on the respiratory system have a relevant role in space-based medical research. The experiments are generally concerned with single or multiple breathing of inert gases. They are mainly related to the distribution of ventilation and to lung vascular apparatus.

After Skylab experiments, only Earth-based simulation techniques have been used, i.e. water immersion, parabolic flights and liquid ventilation in animal models.

Indeed, due to the anatomic and physiologic peculiarities of lungs, during terrestrial simulations the gravitational field acts in a not uniform way on their compartments. For instance, in vertical position apical lobe perfusion is about half the basal one.

This highlights the need to carry out the experiments on the respiratory function in space. Lung functions will be widely studied by a respiratory monitoring system on board Spacelab, by means of a general purpose facility called Anthrorack.

- Animal physiology: cardiovascular and metabolic systems

Another relevant aspect of space medicine concerns fluid behaviour and such electrolytic variations of fluids as the ipohydration occurring during early flight days. A viable explanation may be the re-equilibrium of those fluids which exceed normal values within the tissues.

On ground, blood (arterious) pressure is 100 mm Hg at the heart, it is 200 mm Hg in feet vases and 60 mm Hg in head ones. Indeed, both aorta and carotid contain baroreceptors, which activate vase muscle contractions.

Under microgravity conditions, 0.6 to 2 litres of blood shift from feet to chest and head. This explains astronaut "chicken legs" and "puffy faces".

The shifting also produces heart atria distension. This largely reduces ADH (antidiuretic hormone) and aldosterone secretion, inducing major urine excretion and associate loss of calcium.

During the first days in orbit, the average calculated weight loss is about 2-4 kg. Around the fourth flight day, a re-equilibrium of fluid weight and volume occurs.

The re-equilibrium of fluid volume and of electrolytic concentration may be tightly bound to the regulation of energetic metabolism, endocrinology, liver functions, biomechanics, skeleton, and cardiovascular functions.

Although qualitative observations have been collected in space to date, there are no quantitative data about body subsystem adaptation to 0-g and re-adaptation to 1-g.

- Animal physiology: neurophysiology

Neurophysiological studies in microgravity are mainly concerned with the vestibular apparatus. A lot of

experiments have been carried out on humans and animals in space and in space-simulated conditions.

During SL-1 and SL-D1, for instance, 30 experiments in human neurophysiology have been performed, especially using the SLED facility. Only the helmet was used in the SL-1 mission while the whole facility was available in SL-D1.

The SLED can stimulate dynamic responses of the human vestibular apparatus in man by means of sudden accelerations. The facility can (and did) monitor data about eye movements, body postures and breathing, blood pulse and heart beat rates.

The collected data were integrated by verbal reports of subjective sensations such as motion perception thresholds, including fictitious or illusory sensations.

- Plant Physiology

Plant physiology deals with the modifications in plant growth, reproduction and survival mechanisms in space. Gravity, together with light and nutrients, is one of the major drivers for all plant physiology processes.

Gravity acts on the orientation of various plant organs. This is known as "geotropism", whose most evident effect is root and stalk growth along the gravity vector but opposite to each other.

On Earth, gravitropism can be revealed by putting a root horizontal. Some species display a curvature in the root free extremity just a few minutes after tilting. Gravity-sensitive cells are called "statocytes"; they contain little formations, denser than the surrounding part of the cell, called "amyloplasts".

On ground amyloplasts move towards the lower part of the cell, due to gravity. They produce an overpressure on some organuli (endoplasmatic reticulum, microtubuli, cell membrane).

This in turn stimulates or inhibits cell division through growth hormone production and transport. Areas of faster and slower growth are opposite to each other, across the stem or root axis, so that bending occurs towards the slower growth area.

Conversely, under reduced gravity the amyloplasts are scattered within the statocytes and the growth regulating hormone is uniformly distributed in the plant

organs, thus preventing "earthly" stem and root orientation.

Many space-based experiments have been carried out about seed germination, about small plant growth and morphology, about protoplast (i.e. plant cells without cell membrane) physiology.

Miniaturised closed ecosystems, for instance yeast in aerobic conditions together with green algae, or small animals and plants, have been tentatively reproduced in space.

They are looked at as preliminary closed environment life support systems such as those envisaged for long duration missions. Indeed, human waste recycling by means of plants and bacteria might assure future crews their oxygen and even nutrients (e.g. maltose).

- Cell biology and microbiology

At basic research level, knowledge of 0-g effects in cell biology allows a better understanding of the origin of physiology perturbations due to microgravity in complex organisms and systems, like man, and the development of space biotechnology.

A microgravity influence on bacteria (e.g. enhanced resistance to antibiotics and conjugation) mammalian cells (e.g. negligible proliferation of lymphocytes in presence of mitogens) and protozoa (e.g. enhanced motility) has been demonstrated, in several experiments, using cell culture processes and observing activities by qualitative (e.g. electron microscope) and quantitative (e.g. radioactive labelling) techniques.

There are at least three hypotheses explaining cell behaviour in microgravity. They are briefly described in the following.

- Cell biology: morphology and cell behaviour

Cell shape may depend on gravity and may influence important cell membrane functions such as the transport of nutrients, hormones, mitogens and other types of ligands which bind to receptors.

Some experimental results may be explained this way. Calculations which do not take into account cytoskeleton show that the distribution of cell organuli such as

mitochondria, nucleus, nucleoli and ribosomes is influenced by gravity.

The condition of free movement of such organuli occurs for cells greater than 10 micron. Hence, animal cells may be more sensitive to gravity than bacteria. This has actually been already demonstrated by observations of bacterial activity in hypergravity.

The cells endowed with skeleton and nucleus have a reticulate structure, made up by filaments, called "microtrabecular". This sustains the lengthened structures of the endoplasmic reticulum, the mitochondria, the microtubules and the microfilaments plunged into the cell cortical layer (i.e. the layer immediately under the cell membrane).

The sensitivity of this reticulum to cell environment changes, which is demonstrated by the effects of low temperatures, seems to indicate that it is a physiologically active cell component.

Hence, it may be a very important element of cell graviperception, because any weightlessness-induced morphological variation of the cytoskeleton may produce physiology and functional changes in organuli connected to it.

- Cell biology: gravitational receptors

The presence of gravireceptors within the cells, such as the amiloplasts in the statocytes, that may explain plant behaviour in microgravity, finds no counterpart in microorganisms and animal cells.

Thus, "gravity bio-sensors" generally means large bio-systems which can transfer acceleration information both directly, such as vestibular organs in vertebrates and statocytes in plant roots, and in an indirect way, such as pressure and muscle tension sensors.

Their experimental investigation may be of some importance due to their more sophisticated character and interactions, as compared to baroreceptors and statocytes.

- Cell biology: molecular interactions in microgravity

The existence of variations in molecular mechanisms that are at the basis of cell metabolism may implicate the sensitivity of all organisms to microgravity. The

phenomenon may have different importance depending on the kind of cell and of interaction.

Some space-based experiment results seem to indicate the existence of microgravity-induced cell and cell subsystem biology variations at a molecular level, as suggested by the so-called bifurcation theory.

Indeed, experiments have been performed to test this basic point. They range from bacteria conjugation, to lymphocyte proliferation in presence of mitogens, from differentiation and embryogenesis to cell repair mechanisms and increase of bacteria resistance to antibiotics.

- Biotechnology

An important aspect of micro-organism behaviour in microgravity is the possibility to develop space biotechnology, that is the possibility to manipulate for practical purposes cell physiology on orbit. This is the counterpart of applied material science research.

Biotechnology deals with the possibility of:

- maintaining cells in a controlled and constant environment without suspending them in solutions
 - investigating the energy saved by cells to move and to keep their shape in space
 - testing bacteria resistance to antibiotics
 - varying some cell interaction mechanisms,
- that is of exploiting the space environment for industrial purposes.

The three above mentioned hypotheses about cell behaviour variations in weightlessness, i.e. morphology changes, gravireceptors and molecular interactions, do not exclude each other. Indeed, their combined and simultaneous action looks sometimes possible.

It is generally assumed that (eukaryote) cells which are flat at 1-g turn spherical at 0-g. As this is a minimum cell energy consumption condition, they may save part of the energy they would normally use for mobility and shape conservation on Earth to proliferate and to produce useful biological substances.

The hypothesis of molecular interactions is difficult to accept because gravitational forces are orders of magnitude weaker than electromagnetic ones.

However, the theory by Prigogine and Stengers and the existence of a gravitational contribution to diffusion

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phenomena do suggest a quantitative theoretical explanation to the observed phenomena.

In fact, the Prigogine-Stengers theory implies that microgravity may induce deviations in molecular interactions and that the sum of these deviations may produce a loss of functions of uni- and pluri-cellular systems.

On the other hand, gravity acts on transport processes by increasing the apparent diffusion coefficient through macro- and micro-convective g-dependent contributions. The experimental verification of these perturbations makes up a significant portion of biotechnology.

As an example, the interaction between various substances and DNA may be different in orbit than on Earth. Harmless food/pharmaceutical additives may in this case become dangerous on orbit.

Also, new recombinant DNA techniques may be investigated, exploiting both membrane permeability changes allowing for new vectors and variations of DNA-substance binding characteristics.

Furthermore, microgravity offers other investigation and production opportunities, by improving and using separation (electrophoresis, phase partitioning) and bioproductive (electro cell fusion, cell culture) techniques, together with protein crystal growth (of purified elements).

3.2 PHYSICAL PHENOMENA RELEVANT TO THE EXPERIMENT CLASSES

This paragraph summarizes the physical or physico-chemical phenomena which bear greater relevance to experiment classes reviewed in the previous paragraph.

The aim is to highlight those phenomena which are influenced by gravity and can motivate investigations in a variable gravity environment.

As it will be evident in the following, gravity influence on experiments, even if not completely clarified, is by far much easier to describe in terms of elementary phenomena and much better understood for material science than for biology experiments.

3.2.1 Material sciences experiments

Fluid Statics

Surface tension and gravity act on liquid masses in competition with each other. The former "holds the fluid matter together", while the latter acts as a body force, the weight, and induces deformations and rupture in the fluid volume. Their mutual balance is expressed in the dimensionless number theory by the (static) Bond number.

When a fluid mass is put in rotation, a destabilising effect is produced by the centrifugal forces and the new balance is summarized by the rotational Bond number, or Weber number.

Interfacial effects depend on the relative values of the surface tensions of the fluid(s)/solid in contact. They are functions of the thermodynamic conditions (mechanical equilibrium) and of the chemical species (diffusional equilibrium).

In all the considered configurations, when stability/instability conditions are studied all the potentials relevant to the forces acting on the sample need to be taken into account.

Fluid Dynamics

The main interest in fluid dynamics experiments in microgravity is linked to the transition from (gravity driven) buoyancy convection to the absence of this kind of convection.

The latter permits to study a number of "second order" phenomena, usually unobservable on ground, related to the boundary conditions, to the bulk properties of the fluid(s) (density, viscosity, thermal conductivity, mass diffusivity, surface tension, etc.) and to the superimposed fields.

Owing to the reduction of gravity action, space fluid dynamics is ruled by the competition between inertia forces and viscous drag on one side, and all the motion-inducing forces, on the other side.

At the same time, the importance of convective phenomena related to thermal or solutal fields and activated by gravity (buoyancy/sedimentation) decreases.

Motion is now activated by non uniform thermal and/or solutal fields in presence of a free surface: in this case a variation of the surface tension value along the surface gives rise to a convective motion, called thermal or solutal capillary convection. When both a thermal and a solutal gradient are simultaneously present, the phenomenon is defined thermosolutal convection.

The transition from gravity-driven convection to convection activated by a surface tension gradient is studied as a critical phase.

The above mentioned phenomena can be intrinsically stable or oscillatory depending on the interface geometric configuration and on surface tension dependance on temperature and/or on species concentration. As a consequence, stability analyses make up another important activity chapter.

Surface waves are also a matter of study: they are divided in gravitational, capillaro-gravitational and capillary waves according to whether the prevailing (or equilibrating) effect is that of gravity or of surface tension.

Fluid masses are set in motion, in absence of their own weight, by applying acoustic fields at their boundary surfaces. These experiments evidentiate the competitive roles of inertia, internal viscosity and of surface tension.

Thermodynamics

Thermodynamics and transport properties measurement is possible in space due to the absence of sedimentation, of

density-driven phase-separation and of gravity-driven convection.

In particular, these three conditions are simultaneously required in order to measure transport properties.

In thermodynamics experiments, on the contrary, the temperature is kept uniform over the whole experimental region and the heat transfer rate is very low, even during transient phases. Therefore, the most important effect is the vanishing of the gravity attraction on the fluid layers, which avoids the stratification observed on ground. The reason for this is the divergence of isothermal compressibility near the critical point.

Physical Chemistry

Physico-chemical processes and chemical reactions are influenced in a complex way by gravity, via buoyancy and convective flows.

These add their contribution to heat and matter transport mechanisms which, in the absence of gravity, are limited by pure diffusion.

Chemical pattern formation, for instance, should show high sensitivity to the gravity-driven convection flow due to density variations over the experimental volume.

Thermal buoyancy convection vanishing also improves the measurement of relaxation phenomena which take place after the passage of a ultrasonic wave in a fluid.

Combustion phenomena are essentially influenced in a microgravity environment by the vanishing of convective phenomena linked to the steep thermal gradients.

Therefore, the appeal of a microgravity environment is twofold, because purely diffusive conditions are beneficial to both pure and applied science experiments.

Experimental verification of theoretical assessments about the fundamentals of the phenomena under examination and interesting applied science results can, indeed, be achieved.

For instance, a well known purpose is a realistic representation of fire propagation and extinction dynamics on board space vehicles.

Crystal Growth from Melt

Gravity force reduction benefits to crystal growth from melt are manifold. The main reason of the mentioned bonuses is linked to the suppression of both thermal and solutal buoyancy related convection.

Convection has to be avoided, first of all, because it hampers the possibility to maintain a homogeneous (both longitudinal and radial) dopant concentration in the growing solid portion.

Such a lack of homogeneity induces the so-called macrosegregation which, as indicated by its name, shows up over the whole volume of the crystallised sample.

On the contrary, gravity reduction favours the onset of diffusion controlled regime and, as a consequence, the achievement of a uniform concentration field in the sample.

Besides, convective motions also induce local segregation at the advancing solidification front (microsegregation). Time-dependent, unstable convection is responsible for local perturbations of thermal and solutal fields close to the solid-liquid interface.

These give rise to oscillations in the growth rate and, ultimately, in the dopant concentration in contiguous layers of the crystal (striations).

These irregular, striped zones are avoided when gravity-driven convection is prevented by gravity reduction. The latter, however, also has a parallel negative effect, in that it remarkably lowers the critical conditions for the onset of the oscillatory Marangoni convective flow.

Absence of convection and reduction of contacts with the container walls are considered beneficial also in terms of reduction of dislocation density, of twins and grain boundaries and of global "single crystallinity". It is, however, not yet clear which one of the two abovementioned reasons is prevailing.

Experimental purposes include not only high quality sample production, but, even more important, the study of the phenomena occurring during crystal growth under purely diffusive conditions.

Crystal Growth from Solution

The avoidance of gravity-driven convection due to thermal and/or solutal gradients is the major benefit received by the reduction of gravity level in crystal growth from solution, too.

Diffusion-limited processes allow better samples to be prepared than at 1 g. Higher compositional homogeneity over the whole volume can be achieved and the number of dislocations and included impurities can be reduced since the absence of convection allows a steady solutal field to be maintained.

Also, undesired spontaneous nucleations of low solubility substances in the bulk of the solution are limited in number when convection is missing, because nucleations take place only where diffusion occurs and not all over the growth cell volume, due to convection-promoted mixing of the solutions.

Scientific purposes include, but are not limited to, the production of rare, high quality samples for terrestrial use in advanced, high performance devices.

A parallel, major objective is the possibility to support the experimental validation of theoretical models of growth phenomena in ideal diffusive conditions, without other additional heat and mass transport contributions due to natural or forced (stirring) convection, but for the fluid motions due to possible surface tension gradients.

Crystal Growth from Vapour

As a matter of fact, not many experiment results are presently available; furthermore, a deep and detailed investigation of the process fundamentals is needed. This is indicated as one of the objectives of the future experimental activities in this field.

However, microgravity influence is mainly identified with convective instabilities suppression in the vapour transport process.

Establishing a purely diffusive regime is beneficial to the crystal lattice regularity and to its compositional perfection.

The importance of this is enhanced when one considers that growing large crystals requires large-size reactors; this directly enhances the onset of convective instabilities.

Secondarily, a non negligible benefit comes from the cancellation of the crystal's own weight effects, such as permanent deformations caused by shear stresses during the growth process.

Metals and Alloys Solidification

In the most general situation, metallurgical processes of interest in space are characterised by the solidification process.

There, a mass of liquid metal is subjected to a temperature gradient which induces solid particles nucleation and the subsequent growth of a solid portion.

The interface of the latter which advances towards the liquid shows morphological characteristics well evidenced by the results of directional solidification experiments (plane surface, cellular front, dendritic front,...).

As pointed out in the previous section, the fundamental purpose of space-based metallurgy research (letting aside the aim of preparation of new materials) is the progress in understanding the phenomena related to solidification and in validating their theoretical descriptions.

To this purpose, microgravity permits to "cancel" convective transport contributions due to buoyancy and/or sedimentation; these are caused by thermal and solutal fields generating spatial density variations.

Only gravity-independent transport processes are left, diffusion in the first place and then Marangoni thermal and solutal convections (if free surfaces are present) and finally convective motions directly caused by the advancement of the growing interface and by the volume variation relevant to the liquid-to-solid transformation.

Besides the possibility to eliminate gravity-driven convection, alloys with a miscibility gap in the liquid phase get an essential additional benefit from a microgravity environment.

This consists in the absence of sedimentation effects on the liquid phases with different densities simultaneously present during the crossing of (by cooling), or the permanence in, the liquid state miscibility gap of the phase diagram.

This situation allows solid phase dispersions to be unaffected by sedimentation and convection. This is

important not only in the perspective of preparing new materials with improved properties, but also, and even more, to support and/or validate theoretical explanations of the formation of this kind of alloys.

Composites

Even if globally ascertained, space processed composite feature dependance on gravity levels is itself a subject for research activities.

In general, it can be stated that fluid dynamics of monophasic or polyphasic liquids, the solidification process and a certain number of physico-chemical processes (reaction mechanisms) are influenced by gravity.

Buoyancy and sedimentation affect microstructure regularity and produce agglomeration and coalescence, while convection influences thermal and solutal fields in the fluid phase.

In particular, for in situ composites:

unidirectionally solidified eutectic alloys need purely diffusive, convection-free for reference experiments to validate theories on the expected values of the interlamellar spacing;

for peritectic alloys microgravity influence is not yet sufficiently clarified;

for monotectic alloys, purely diffusive conditions are required to reach extreme regularity in the fibrous or globular structures and, more generally, to permit easier study of the solidification conditions in absence of gravity driven convective motions.

In the artificial composites group, particle/fibre dispersion stability is improved by the absence of buoyancy and sedimentation which, on ground, generate displacement and agglomeration of the added solid phase. To this purpose also thermal convection is beneficial.

Controlled density materials (gas-bubble-filled materials, metallic foams) are influenced mainly via sedimentation/buoyancy effects, which induce gas-liquid separation, and liquid drainage.

Indeed, gravity elimination is useful for easy exploration of the remnant physical phenomena influencing the foamy material stability (diffusion, Marangoni convection, viscosity effects,...), too.

Glasses

Glass formation in microgravity is mainly, and positively affected by the suppression of the contact between the melt and the container walls, the so-called containerless technique. This prevents heterogeneous nucleation phenomena, that is nucleation due to the action of the container walls.

This technique greatly benefits from the intrinsic gravity reduction effects: the melt bulk weight reduction makes its lifting and positioning inside the process chamber possible or easier.

Additional benefits to the homogeneous nucleation come from the reduction of convective motions inside the fluid mass. This can, however, hamper (in non metallic glasses) glass melt homogenisation and gas bubble final elimination (fining), and it implies the need for preliminary homogenisation of the mixture and adoption of a gas-free starting materials (sol-gel processed materials).

Bioseparation

Electrophoresis by means of the continuous flow method is mainly affected by the fluid disturbances which perturb the sample fractions trajectories within the chamber.

Out of these disturbances, buoyancy due to thermal gradients is not avoidable on ground and impacts by convective motions on the streams of the separated fractions.

Therefore, microgravity benefits appear as buoyancy convection suppression.

Isoelectric focusing method seems to be sensitive to the same problems, i.e. convective disturbances during the separation migration across the chamber. Experimental findings, however, are not sufficiently clarified.

Phase partitioning seems to be benefiting from a buoyancy-free environment because the purely thermodynamical cell separation process between the phases is not disturbed.

3.2.2 Life sciences experiments

As already anticipated, defining the mechanisms by which gravity acts on animals, plants and cells is not easy, even letting aside their quantitative description.

This rather unclear and involved situation compelled to introduce a detailed description of the related phenomenology already in the paragraph relevant to the experimental area description.

The following considerations are, therefore, just a summary of the already described phenomena.

Animal physiology and related areas, such as health care, maintenance and medicine: weightlessness macroscopic effects substantially consist of body fluids redistribution, of the associate effect on the baroreceptors and of the loss of competitive effect of weight on muscles, bones and internal organs. All of them directly affect animal (and human) physiology.

Plant physiology: top-level effects are the consequence of cell gravireceptors functions inhibition due to the suppression of buoyancy and sedimentation. This eliminates one of the three plant growth drivers, gravitropism; the other two, chemio- and photo-tropism can be gauged to assess their mutual interplay.

Cell biology: several hypotheses are proposed to explain gravity effects on cell life, reproduction and genetics, namely: morphological changes in the cell due to own weight loss; absence of gravity influence gravity sensors (gravireceptors); direct gravity field interaction at a molecular level.

Biotechnology: cell cultivation is influenced by the absence of sedimentation of cells with different densities; electro-cell-fusion might exploit gravity related cell morphology changes.

3.3 EXPERIMENTS AND PHYSICAL PROCESSES SIGNIFICANT TO VARIABLE GRAVITY

This chapter contains the preliminary identification of those experiments for which providing a variable gravity environment may be significant.

The points brought up in this chapter were selected after a critical review and analysis of the literature about microgravity experiments (see previous sections) and after a round of contacts with selected experts.

The considerations exposed here were subsequently taken into account during the subsequent variable gravity laboratory performance definition activities.

The scientific interest is preminent in microgravity over the immediate industrial production purposes. Exploitation of microgravity is intended (in Europe) mainly for pure and applied science, the aim being at increasing basic scientific knowledge about several basic aspects of the phenomena under study. As a secondary goal, the provision of guidelines for ground-based material processing.

As testified by the wide set of past mission data, experiments have so far been performed under rigidly prefixed g-level conditions (disturbances included).

Sometimes these are not the best conditions to achieve the experiment purposes and they never allow an assessment of physical processes parametric dependance on the g-level.

For instance, transitions between different prevailing flow conditions or instabilities onset could not be observed.

Another forbidden objective is the provision of further experimental results, at different residual gravity, concerning certain physical effects which are not completely clarified or sufficiently measured or, even, whose presence is uncertain at all.

Past and present literature on the subject contains only very scarce explicit suggestions concerning experiments under variable gravity conditions.

Indeed, only generic statements are found, without any further definition of detailed experiment sequences or even only of specific experiment areas.

Therefore, it was assumed that the primary objective would be the repetition of the experiment runs at different

steady g-levels; the g-level would have to be kept constant during each run.

This was deemed adequate for validating existing theories, for extending the existing data to different g-levels, for detecting evidence of significant differences from fixed reference g-level and for clarifying unresolved issues from previous results.

More exotic g-profiles time dependance was considered a less immediate request in the present panorama of interests in microgravity experimentation, except for pure (monochromatic) jitter response analysis and for verification of possible hysteresis phenomena (g-cycling).

Indeed, phenomena related to different steady g levels have to be fully understood (which is not the case to date) before more involved and difficult time-dependent g fields can be studied.

The original approach based on the analysis of the theoretical literature to define the g-profiles turned out to be impractical and, even worse, not exhaustive.

Indeed, no detailed process definition was found and, in addition, the search for an "optimum" reduced gravity level for each physical process was recognised not to be sufficient to fully support the definition of the experiments gravity profiles.

As a matter of fact, the search for and the performance at the most appropriate residual gravity level is just one of the possible uses of the variable gravity laboratory.

Performing (many) experiment runs far away from "optimum" conditions, i.e. under "no gravity negative influence", turned out to be a possible requirement.

Indeed, the investigators may be looking for evidence of intermediate conditions due to deliberately introduced "gravitational pollution" .

Alternatively, they may want to approach by subsequent approximations the unknown, theoretically unpredicted best conditions starting from a trial configuration.

This may be the case, for instance, with the transition between purely diffusive optimal regime and purely convective terrestrial regimes in metallurgy and in crystal growth.

Since it was, and still is, impossible either to deduce such purposes from the proposed theories or to extract

them from the available literature, the attention was thus shifted to the interviews with the scientists, supported by the knowledge of the available theoretical results, in order to receive direct indication of their interests.

It is important to point out that the best descriptor of the needs of each experimental area - at least for constant g-level experimentation - is not perhaps the usual line in the g vs. time plane (the so-called g-profile).

First of all, mathematical models and equations correlate physical variables or nondimensional numbers among each other in a complex way. Velocities, concentrations, temperatures, geometrical dimensions, thermodynamical and transport properties (density, thermal conductivity, mass diffusivity, viscosity, surface tension and so on) are linked with each other.

Experiments under variable gravity conditions do not amount to verifying the g-dependance of one physical variable at a time once all the others are assigned fixed values.

Each variable parametrically depends on all the remaining ones; any variation of each of them changes the g value which reproduces the unmodified phenomenon.

It is worth illustrating this point by means of an example taken from Langbein's work (see ref.). The experiments on the Soret effect tolerate (low frequency) g-levels higher by a factor 10^4 when the significant dimension of the diffusion tube is reduced by a factor 10^2 (all the other variables being unchanged).

In this light, a linear g profile versus time can describe only one of the infinite experimental configurations, with defined boundaries and initial conditions and a predefined time evolution.

Therefore, this approach does not look suitable to provide a general definition of the needs of an experimental area, where several kinds of substances, different physical and geometrical conditions are met and different time histories are studied.

As a consequence not only one g-level, but a whole of g-levels (a "bandlike" ensemble), is relevant to the same physical situation (e.g. a transition between different motion conditions, an instability onset, any predetermined thermal or solutal field configuration and so forth) just because of a variation in material properties, field variables and geometry.

Further degrees of freedom are added when the examination is extended to regions whose extension is defined by the independent variation (even within pre-defined limits) of one or more of the involved physical variables.

One example will help clarifying the matter. For the study of the diffusive heat and mass transport conditions which prevail in a medium over the convective ones, the constraints on temperatures and concentrations change from a defined set of specific values (describing a well defined situation) to continuous ensembles of mutually compatible values.

A linear g-profile, therefore, is not adequate to provide a synthesis of microgravity experiment requirements and, ultimately, to answer questions like: "Over which gravity levels is it worth to work, for each experimental area?"

A reasonably simple and straightforward answer based on the reviewed literature and on the undertaken contacts is: "Over the band ranging between two defined values". This was finally selected as a proper requirement definition.

This was also done because so far no mathematical theories predicting the g-level dependance of the phenomena are available for all the experimental areas. In addition, geometrical approximations and physical simplifications imply the need for prediction experimental validation against the real geometrical and physical complexity.

It is noted that sometimes predictions and experimental evidence are in complete disagreement with each other. For instance, $10^{-2} g_0$ is referred as good enough for combustion experiments, while theoretical studies provide a requirement as low as $10^{-7} g_0$ (ref.: 37th ESA Material/Fluid Science Working Group minutes, p.9).

It is, therefore, legitimate to reverse the statement "definition of the variable gravity laboratory expected performances by means of microgravity theoretical studies" into "use of variable gravity laboratory to provide/check experimental data when theoretical predictions are not available or dependable".

This being the situation, only limited help may come from theories in terms of precise definition of g-bands boundary levels for experiments in variable gravity.

The considerations illustrated so far eventually suggested the adoption of the following working method. A direct screening of the opinion/interest of a selected group of

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the scientists involved in microgravity activity (mainly in Europe) was performed.

As a basis for the discussion, the results of the previously performed review were taken, and support was sought in the available and applicable theoretical assessments.

Therefore, the following paragraphs contain the results of the above-described investigation. This was performed, within time and funding constraints, over the telephone, by means of short written questionnaires and, when possible, of meetings with the scientists.

Due also to the preliminary character of the present investigation, the results are not totally conclusive.

They are, however, fairly complete, despite the difficulties inherent in fully describing the complex and inter-related requirements set forth by each experimental area for the research in variable gravity.

Also, microgravity research is in-progress and the whole of its scientific goals is not even completely defined up to now but will need activity results to become so.

This fact, too, implies that the results of the present investigation are intrinsically "open" to future verification, integration and refinement. They should not be used as final and frozen design requirements.

Moreover, a decisive cause is identified in the relative novelty of the "variable gravity" option, a fact which often retains scientists from giving, in a short time, precise indications, compelling their answers within preliminary interest statements, needing further deepening.

The very potential interest expressed by several investigators suggests that this matter may deserve a further, deeper examination by means of an accurate and widely diffused questionnaire. This would have to be delivered with a suitable lead time before to allow adequate understanding and evaluation. This suggestion is taken up in the conclusions.

3.3.1 Material sciences experiments

Most of the experiment topics which would benefit from a variable gravity environment are found under this heading.

As already pointed out, accurate definitions and detailed descriptions of experimental phases and configurations could not be obtained.

Usually, only a preliminary evaluation of possible areas of interest and the exclusion of certain fields or techniques were obtained; quite often no explicit determination of the required associated g-bands could be obtained.

This is most likely due to the new character of this matter and it underlines the difficulties encountered by scientists in replying to specific and detailed questions about it.

Fluid statics and dynamics

Applied fluid mechanics deals with the definition of the behaviour of the fluids stored within containers, sloshing effects in tanks and so on. In this field, only a minor, possible interest was ascertained.

Conversely, great interest is evidenced in the remnant of this area, with emphasis extending possibly to the whole gravity level range.

Concerning fluid statics, the liquid-to-solid contact angle dependance on gravity could be studied ("mapped") experimentally and hysteresis effects, if any, could be detected.

In fluid dynamics, the transition region from buoyant to Marangoni convection was pinpointed as a very promising subject, as well as the possibility to observe the influence of the different g-levels on motion instabilities onset and evolution.

The analysis of the effects of jitter or of similar prolonged disturbances (such as vibrations) on fluid volumes is also suggested. Such analyses would be aimed at evaluating flow, thermal and solutal field perturbations and distortions, relaxation modes and times and instability onset.

Analogous experiments concerning the behaviour of inclusions such as, e.g., bubbles or particles into fluid masses are proposed.

A wide range of gravity levels is preliminarily required, up $10^{-2} g_0$.

Thermodynamics and critical point phenomena

A high interest in variable gravity was ascertained in this area; the availability of different, constant gravity levels for hours to repeat experimental runs looked very attractive to researchers in this field.

Even if a generic interest was expressed in the whole g level projected range, the lower portion, from 10^{-4} down to $10^{-6} g_0$, is felt as the most useful because the constraints over the remaining physical variables (i.e.: temperature) near the critical point can be relaxed.

Ultrasonic wave adsorption in molten salts is, for instance, a typical open issue. The adsorption increases under reduced gravity: this, however, can not be attributed to the absence of buoyant thermal convection. No plausible explanation is known to date and variable gravity is judged as a promising tool.

The investigations of critical point phenomena and spinodal decomposition with kinetics of phase separation would also benefit from variable gravity as, for instance, data may be obtained to discuss correlation length and so forth.

A different aspect is evidenced in experiments dealing with heat transfer and boiling points, where the possibility to exploit variable g -levels allows to make some engineering aspects of the process lighter, such as heating plate geometry and so on.

Jitter analysis was not proposed in this field.

Transport properties measurement

No request for variable gravity was evidenced in this sector of microgravity activities, as no g -dependent phenomenon to be clarified is pointed out.

Measuring molten metals or salts diffusion coefficients just requires that buoyant convection onset is avoided; in some experimental configurations, this may require lower levels than presently exploited but not variable gravity as such.

Jitter analysis was not considered an important aim.

Physical chemistry and applied chemistry

The small number of experimental results hampers the definition of experimental aims in variable gravity. Future activities in this area may, however, call for parametric variations of gravity levels so that the definition of appropriate experimental conditions is possible.

Combustion

The possibility to exploit the range from 10^{-1} to 10^{-4} g_0 was stressed to test the validity of some combustion physical models.

These deal with the case when the steady gravity level is such that the competition between residual convection and diffusion contributions to heat and mass transport is observed. Jitter analysis was not explicitly required.

Crystal growth from vapour

Steady g-levels ranging from 10^{-2} to 10^{-5} g_0 are preliminarily indicated as interesting, with the goal to define the most appropriate growth conditions. Each g level should be kept steady for durations up to a few weeks.

It is pointed out that this experimental approach requires a very good control of the boundary conditions and a precise setting of all the growth process thermodynamic conditions. This in order that the measured deviations in the produced sample characteristics can reliably and correctly be linked to the g-level bias, whose strict constancy over time should be maintained.

Analyses of the g-jitter are discouraged because analysing and understanding jitter effects on the samples is deemed very difficult.

Crystal growth from solution

The possibility to gauge the residual gravity-driven convection is pointed out as a valid tool in order to overcome the limits imposed to growth rate by the purely diffusive heat and mass transfers. The standing constraint

is, of course, that such a residual convection should not jeopardise crystal purity and perfection.

Jitter and vibration effects on the growing crystal can be evaluated.

Another interesting problem is related to the study of the creation of such defects as dislocations and growth bands in crystals moving (due to residual gravity) during growth in a solution after spontaneous nucleation.

Consequent solutal field anomalies may induce supersaturation jumps which would cause, in turn, the mentioned defects. The study of similar effects due to g-jitters is suggested, too.

As a preliminary evaluation, steady levels between 10^{-3} and $10^{-5} g_0$ may be required to achieve the latter goal, while a wider band extending up to $10^{-2} g_0$ may be required to achieve the former one.

As far as protein crystallisation is concerned, the highlighted essential requirement is establishing purely diffusive mass transfer conditions and avoiding different density liquid phases mixing.

This is satisfactorily obtained when gravity is reduced below 10^{-3} or $10^{-4} g_0$, the usual values of space carriers like Spacelab or re-entry capsules.

No dark area was pointed out, at least for the time being, worth exploring under variable gravity conditions. The reduction of noise and vibrations promised by a tethered elevator was, however, considered a nice bonus.

Crystal growth from melt

In the field of crystal growth from melt field, the validation of different physical models concerning the growth process is suggested; in this case, the g-level should be considered as a parameter.

Additional subjects are the effect of a different steady g-level on segregation and on the solutal field in the melted part of the sample during solidification at a constant growth rate. The amount of lateral segregation can also be studied, as it also depends on the residual acceleration direction.

The study of jitter and vibration effects at various frequencies, over different steady g-levels is also proposed.

The full range of g-levels is considered applicable as a first step, due to the difficulty experienced by the scientists in making previsions. The higher part of the range (up to $10^{-1} g_0$) is judged interesting for studies about the transition to the convection region.

Metallurgy: Metals and Alloys

Metallurgists are potentially interested in exploiting variable gravity. They pointed out, however, that interpreting the results could be quite difficult, due to the complexity of the involved phenomena (interaction of thermal and solutal fields, interface effects and morphological features of the growing and advancing solidification front).

Additional difficulties may be raised by the sample opaqueness. This may require employing transparent media with equivalent solidification behaviour in order to visualise the growth phenomena in real time.

Nevertheless, morphological stability under various conditions, including g level variation as a parameter, is considered important.

Variable gravity could also provide a proper tool to investigate some physico-chemical phenomena which depend on the interface tension between the components of the sample.

The chance to explore regions with convective or convecto-diffusive prevailing conditions in the sample fluid portion, together with the intermediate transitions, is considered attractive, implying the request of steady g-levels up to values as high as $10^{-1} g_0$.

The influence of the residual gravity direction is pointed out as an important subject of experimental activity, as well as the effect of jitters.

Metallurgy: Composites

Composites production in space shows some dark areas, where the interaction of several physical and

physico-chemical effects has not been fully understood up to now.

Performing solidification experiments in variable gravity may bring a contribution to further understanding.

Again, however, the separation and the quantitative evaluation of the different effects due to the action of gravity may result quite a difficult task.

Glasses

Only potential interest was declared about glass production in space, but no practical aim has been identified so far. Since glasses are usually dealt with by means of containerless techniques and over relatively short times (hours as a maximum), they are substantially insensitive both to steady residual acceleration shifts and to (limited amplitude) jitters on the facility.

No dark area to be investigated by making g-level a variable was singled out.

Undesired convective motions and contact with the facility walls are satisfactorily avoided on the presently available space carriers.

Separation techniques for biological materials

In this area no particular need to perform experiments in variable gravity was evidenced.

Electrophoresis needs that the internal flow paths are not perturbed by buoyant convection. Below a given g-level this is achieved and no further requirement exists either in terms of gravity field level and orientation or of jitter analysis.

3.3.2 Life sciences experiments

It is not clear whether life science experiments can, on the whole, take advantage of a variable gravity laboratory, even if some general interest was raised in the science community by the concept of variable gravity.

Animal physiology

As far as large living systems are considered, both animal and human beings would find it very difficult to maintain an assigned reduced gravity level.

As first, long term effects of gravity reduction require a long duration exposure. A human being or an animal can hardly be kept for extended periods (days or weeks) inside a limited resource environment with the additional constraint of a high degree of inactivity not to perturb the imposed reduced g-level by body movements.

Animals do move by their own nature and people are known to be stressed by prolonged inactivity in space beyond their psychological limits.

In addition, such internal vital functions as, e.g., blood circulation and heart throb jeopardise the concept of "pure" gravity level exposure, due to the superposition of all the internally generated mechanical disturbances. The lower the reference "external" g-level is set, the more important this aspect becomes.

Furthermore, substantial macroscopic alterations due to weight losses already occur very close to the g level range lower limit, perhaps within the first decade. The rest of the range may, thus, be of little relevance for this study branch.

Likewise, the possibility to create and exploit "artificial" gravity for (quasi) terrestrial life conditions simulation during long duration missions in space does not look realistic.

Jitter effect analysis does not seem to be a goal in this field.

Plant physiology

Plant gravitropism is expected to deserve attention in variable gravity: not only the very thresholds of the phenomena studied under this heading are unknown, but

other dark areas exist which are pointed out as needing investigation.

The repetition of experiments intended to ascertain gravitropism thresholds or differently shaped g-dependance requires the availability of constant g-levels for periods ranging from hours to days for each experiment run, depending on the kind of botanic sample.

Even though 10^{-1} to $10^{-4} g_0$ is the range where a general consent places the gravitropism threshold, additional interest in the decades closer to the lower end of the full range is evidenced by contacts [with prof. A.Brown].

It is underlined that these g-levels are only attainable by means of the tethered elevator; centrifuges can reach down to $10^{-4} g_0$, as per, for instance, the expected performances of NASA's VSMDC - Variable Speed Mid Deck Centrifuge - presently under design.

No particular interest in pure jitter response observation has been found, while a possible subject is the understanding whether and how plants "learn" to react to gravity stimulus [A. Brown]. Investigating whether they modify their gravitropistic response after experiencing a different g-level may involve an elevator-based facility.

Also suitable for experimentation in variable gravity is the definition of the gravitropistic response dependance on the intensity of the gravity field and on its temporal duration.

Cell biology and biotechnology

On the whole, scientist look convinced that cell biology studies could not be benefited very much by the advent of a tethered elevator. This even though, in line of principle, biological phenomena activation threshold identification is one of the main objectives in life sciences.

As a matter of fact, such thresholds are believed to be set at g levels closer to g_0 , most likely in the first and in the second decade. These are the least accessible values for a tethered elevator.

On the contrary, present and future centrifuges may rather easily provide adequate g levels and enough room to host the (usually small) sample containers employed in cell biology experiments.

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The need for time dependent gravity has not been evidenced for the time being; the projected set of discrete, steady levels is deemed sufficient to the present users' needs.

Tethered elevators may, however, serve a different purpose, unrelated to variable gravity: the possibility to expose living matter to the external environment in regions of the space which do not consent orbital permanence.

Response to radiations, near-vacuum conditions and, possibly, exposure to magnetic fields are evidenced as interesting though appropriate to exobiology and radiobiology and not, strictly speaking, to microgravity.

Cell cultivation and genetic engineering may look at variable gravity as at a possible future environment where results coming from basic science advancement in cell biology may be applied to optimise qualitative and quantitative results.

Therefore, this application looks a follow-on possibility, to be, however, considered in case the tethered elevator is preferred to a centrifuge because of sample dimensions, complicate or difficult operation or so.

Electro-cell-fusion techniques do not seem to be directly benefitting from the variable gravity option.

4.0 TETHERED VARIABLE GRAVITY LABORATORY PROPOSED EXPERIMENTS

This chapter provides a synthesis of the results emerged during the study and discussed in the previous chapter.

Para 4.1 summarises the mentioned results under the form of a table; when possible, the quantitative information relevant to each experimental area is also provided.

Para 4.2 details the requirements imposed on the residual acceleration field affecting the variable gravity laboratory, together with its acceleration monitoring and recording expected capabilities.

4.1 EXPERIMENTS REQUIRING CONTROLLED g-LEVEL VARIATIONS

The following table is intended to provide a synthesis and a synopsis of what has been dealt with in the previous chapter, thus answering the request for "gravity profiles".

For each main experimental area, the possible interest in the variable gravity tethered-based laboratory, its preferred use, the useful gravity level "bands" and the experiment maximum expected durations (order of magnitude) are shown.

The last two descriptors enable envelopes of possible experiments to be derived in the gravity vs. time plane.

The preliminary character of the displayed information ought to be borne in mind; further and deeper investigation is expected to complete, modify and improve in precision and detail the data and the categories hereafter shown.

In addition, no explicit, clearcut request for time depending variable gravity has been set forth up to now. This is true both in terms of clear indications of topics (exception made for the problem of the fluid(s)/solid contact angles) and of related gravity versus time profiles. Therefore, this option is not present in the table.

An explicit ranking of the interested experiments does not appear appropriate at the moment. It is, however, easy to derive from the table itself the relative specific interest of each area.

EXPERIMENT CLASSES	benefit from variable gravity teth.lab	prefer- red utili- sation option	useful g-level band (g/g ₀)	experi- ment duration (order of magnitude)
FLUID STATICS & DYNAMICS	Y	S,J	10 ⁻² ÷10 ⁻⁶	up to hours
THERMODYNAMICS & CRI- TICAL POINT PHENOMENA	Y	S	10 ⁻⁴ ÷10 ⁻⁶	hours
TRANSPORT PROPERTIES	N	=	=	=
PHYSICAL CHEMISTRY	Y(TBV)	S	TBD	hours(TBV)
COMBUSTION	Y	S	10 ⁻¹ ÷10 ⁻⁴	min+hours
CRYSTAL GROWTH FROM VAPOUR	Y	S	10 ⁻² ÷10 ⁻⁵	up to weeks
CRYSTAL GROWTH FROM SOLUTION	Y	S,J	10 ⁻² ÷10 ⁻⁵	days
PROTEIN CRYSTALLISAT.	N	=	=	=
CRYSTAL GROWTH FROM MELT	Y	S,J	10 ⁻¹ ÷10 ⁻⁶	hours to days
METALLURGY: METALS, ALLOYS AND COMPOSITES	Y	S,J	10 ⁻¹ ÷10 ⁻⁶	hours to days
GLASSES	N	=	=	=
SEPARATIVE TECHNIQUES	N	=	=	=
ANIMAL PHYSIOLOGY	N	=	=	=
PLANT PHYSIOLOGY	P	S	10 ⁻⁴ ÷10 ⁻⁶	days to weeks
CELL BIOLOGY	N/(*)	(*)	N/A	TBD
BIOTECHNOLOGY	P(TBV)	S(?)	TBD	TBD

NOTES: Y = yes; N = no; P = possible;
S = steady levels; J = jitter or vibration response;
TBD = to be defined; TBV = to be verified
(*) : benefits from variable gravity lab are a quite remote
possibility; exo- and radio-biology are possible.

4.2 BASIC REQUIREMENTS ON A TETHERED VARIABLE LABORATORY

As a preliminary outcome from the performed assessment of the variable gravity related experiments, a first set of requirements was formulated.

This also took into account that the space elevator-based laboratory is likely to be, by its own nature, limited in terms of resources and - at least in the first operative phases - of operational time.

Thence, the assumed utilisation philosophy suggested to privilege, as a conceptual baseline, the idea of a single facility carrier, capable to support the repetition of the experiments on different experimental samples or on renewed experimental media at each subsequent different specified gravity level, without intermediate retrievals to the Mother Station.

A single facility configuration should avoid crossed interferences among different experiments running in parallel. At the same time, dedicating the whole resource budget to a single facility should allow a rich and complete set of stimuli actuators, diagnostics means and recording capabilities to be present on board.

This configuration should be suitable to fully exploit the features of this unique experimental tool, that is the possibility to attain unusual experimental conditions with complete environment monitoring.

Fixed experimental conditions, high costs, limited operational times and, even more, little environment monitoring characterise the existing carriers.

Any cause of possible pollution of the environment, above all the gravitational one, should be avoided, not to be compelled to discard spoiled results and to repeat observations.

Likewise, care should be taken against inadequate provisions of stimuli and instrumentation and possible shortage of (physical and functional) resources.

In order to match the currently known investigators expectations, the following preliminary requirements are proposed, concerning residual acceleration environment features and monitoring:

- full (quasi-)steady residual acceleration level range:
 10^{-6} to $10^{-1} g_0$;

- within the abovementioned range, availability of discrete levels spaced from each other by no more than half an order of magnitude, namely:
 10^{-6} , 5×10^{-6} , 10^{-5} , $5 \times 10^{-5} g_0$ and so on;
- residual acceleration dependance on frequency as follows:
 - (quasi-)steady, frequency $f < 1$ Hz:
constant, with disturbances allowed to be within 10% of the nominal value;
 - low frequency, $1 \text{ Hz} < f < 100 \text{ Hz}$:
matched linear increase with frequency;
 - high frequency, $f > 100 \text{ Hz}$:
matched quadratic increase with frequency;
- permanence at each specified level: up to 15 days;
- no gravity level continuous variation with time;
- residual acceleration vector direction to remain within a circular cone whose semi-aperture angle is 1 degree (TBV) and whose axis is the experiment significant direction (e.g.: the normal to the plane solidification front); capability to accommodate changes of the significant direction;
- g-jitter generator provision;
- laboratory triaxial acceleration monitoring:
 - * range: 10^{-7} to $10^{-1} g_0$
 - * frequency band: 10^{-2} to 10^{+2} Hz
 - * accuracy: $\leq 10\%$ of the measure(not necessarily by means of the same instrument);
- experiment acceleration monitoring capabilities, in the desired amplitude & frequency ranges, are assumed to be part of the laboratory-mounted experiment itself, as close as possible to the site where the experiment takes place. This in order to discriminate between experiment own and environmental effects. This is a very critical, delicate, and so far underestimated, subject.

Since the above preliminary requirements are related to the experiment-required/recommended gravity profiles, the former may undergo modifications and refinements if supplementary investigations are carried out.

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Indeed, a more complete microgravity user familiarization with the new concept and the subsequent collection of a wider set of more detailed suggestions may, indeed, lead to a more precise definition of the performances of the variable gravity carrier.

In particular, requirements for continuously varying g level time dependance may develop, following the definition of the corresponding experimental purposes and features.

5.0 CONCLUSIONS AND RECOMMENDATIONS

A tethered elevator can provide an almost unique dynamical environment, because the residual acceleration levels can be tuned in value, duration and orientation.

This constitutes an extension of the capabilities currently offered by the space based centrifuges which, however, do not show a flawless performance. Indeed, the Coriolis acceleration and the centrifugal force gradient limit their effectiveness as supports for microgravity experiments.

Researchers in microgravity science fields presently consider that space offers a highly attractive possibility to answer a lot of open questions concerning basic aspects in pure sciences and very interesting topics in applied sciences.

The prevailing trend, particularly in Europe, is to exploit space based experiment to construct and validate theories and to support materials production or biotechnology applications.

On the contrary, weightlessness exploitation for large scale materials production is considered, for the time being, substantially premature. On the other hand, other promising production areas, such as electrophoretic separation, seem to be showing results inferior to the expectations.

In this perspective, it is reasonable to foresee that variable gravity may essentially be seen as an additional, complementary tool supporting fixed g-level research.

Even if hints exist in the literature about the potential utility of gravity fields continuously variable with time, no experiment targets have been precisely defined for the moment.

In addition, it was suggested that a full understanding of gravity effects over a broad range of discrete and steady g-levels ought to be achieved before the investigation of the very complex ones due to non steady gravity can be started.

Thus, according to the results shown in the previous sections, the prime utilisation mode of a variable gravity laboratory should be the steady g-level mode, with performances capable to fulfill the above shown requirements.

It is worth reminding that particular attention should be paid to avoiding that spurious effects due to unwanted variation of the other physical factors may pollute those induced by g-level variations, as the attempt to decouple them is a really hard task.

In the assumption that the above is adequately taken care of, subsequent utilisation phases may well foresee the inclusion of residual acceleration continuous variability with time in the capabilities of the variable gravity laboratory, provided the relevant experiment sequences are outlined.

Even if the screening of the topics benefiting from variable gravity may be completed and refined in the future, quite a number of applications would clearly benefit from such an environment, mainly in fluids and materials sciences. Conversely, a tethered laboratory looks far less appealing to life sciences disciplines.

The findings illustrated in this report prove that there is room for a variable gravity tethered laboratory among microgravity experiment tools.

This is, however, a new concept and most researchers have no familiarity with it, which makes it difficult to collect detailed requirements, particularly concerning performances and resources.

Also, theories in support of such a new experiment opportunity are still very few and debatable. As a consequence, the original plan to obtain the applicable requirements from them could not be followed.

Therefore, the overview of possible experimental subjects, the associated descriptors (g-level bands and time durations), and the consequent g-environment requirements are all preliminary and may well undergo future modifications, additions and refinements.

Indeed, possible future activities of this kind may require a very broad distribution of information on possible or projected variable gravity laboratory features to be verified, later on, by means of detailed questionnaires.

The importance of clear and detailed information about the variable gravity option as a support to investigator brainstorming can not be emphasized enough.

Needless to say, completion and refinement of theoretical analyses and related computer simulations concerning gravity effects would be highly helpful.

6.0 APPENDICES

6.1 REFERENCES

The following literature about experimentation in microgravity or about related basic subjects was used in preparation to this report.

Microgravity missions reports or scientific meetings proceedings

"Material sciences under microgravity"

proceedings of the European Symposia:

1st: Frascati, Italy, March 1974; ESRO SP-101

2nd: Frascati, Italy, April 1976; ESA SP-114

3rd: Grenoble, France, April 1979; ESA SP-142

4th: Madrid, Spain, April 1983 ; ESA SP-191

5th: Schloss Elmau, West Germany, November 1984;
ESA SP-222 (Results of Spacelab-1)

6th: Bordeaux, France, December 1986; ESA SP-256

"Fluid dynamics and space" ESA SP-265

proceedings of Jun.86 ESA-sponsored symposium

"The Effect of Gravity on the Solidification of Immiscible Alloys" ESA-219

proceedings of the RIT/ESA/SSC Workshop, Jaerva Krog, Sweden, January 1984

"ESA - 37th meeting of the MATERIAL SCIENCE/FLUID SCIENCES WORKING GROUP - 29 June 1988 - ESA HQ, Paris" MS/FS-WG/MIN/37; Paris, 29 September 1988

"Life sciences research in space"

proceedings of the European Symposia:

1st: Cologne, Germany, May 1977; ESA SP-130

2nd: Porz Wahn, Germany, June 1984; ESA SP-212

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- "Material sciences in space",
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Numbers dedicated to Material Sciences:
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Pergamon Press

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- "Crystal growth"
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- "Phisique theorique, tome VI: mecanique des fluides"
L.Landau, E.Lifchitz
MIR Publisher, Moscow, 1971

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- "Allowable g-levels for Microgravity Payloads" - ESA
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publication in ESA journal)
D.Langbein - Battelle Institute e. V., Frankfurt/Main
- "g-level threshold determination" - Techno System Report
TS-7-84, june 84
R.Monti, study manager
- "Allowable g-levels for Spacelab, COLUMBUS and EURECA" -
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april 1987
D.Langbein - Battelle Institut
. WP 1 - Battelle - Frankfurt
. WP 2 - CEA/CENG - Grenoble
. WP 3 - Techno System - Napoli

6.2 EXPERTS/INSTITUTIONS CONSIDERED FOR CONTACTS

The following lists include all the individuals and institutions taken in consideration since the beginning of the study for contacts aimed at receiving information and materials relevant to the study purposes or to provide suggestions and validations about basic scientific features and/or study assessments.

Underlined names correspond to the contacts actually performed.

In Italy:

- Istituto di Mineralogia,
Universita' di Genova
prof. F.Bedarida (Crystal Growth from Solution)
- Istituto di Chimica Fisica Applicata ai Materiali,
CNR, Genova dr. A.Passerone (Metallurgy)
- Politecnico di Milano
prof. F.Rossitto (Materials Science)
- Istituto di Aerodinamica "U.Nobile",
Universita' di Napoli
prof. L.G.Napolitano, prof. R.Monti (Fluid Physics)
- Universita' di Roma II
prof. P.Gondi (Metallurgy)
- Universita' di Roma
prof. A.Scano, dr. F.Strollo (Human Physiology)
- Universita' di Milano
prof. P.G.Righetti (Biotechnology - Electrophoresis)
- Universita' di Pavia
prof. O.Tiboni, prof. O.Ciferri (Microbiology)

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In Europe:

- NLR (The Netherlands)
prof. J.P.B.Vreeburg (Fluid Physics)
- Polytechnic University of Madrid
prof. I.Da Riva (Fluid Physics)
- Battelle Institut (Frankfurt-am-Main)
prof. D.Langbein (Fluid Physics)
- University of Bruxelles
prof. J.C.Legros (Physical Chemistry)
- CEA-CENG Grenoble (France)
prof. Y.Malmejac, dr. J.J.Favier (Metallurgy and
Crystal Growth from Melt)
- ETH - Swiss Federal Institute of Technology of Zurich
prof. E.Kaldis (Crystal Growth from Vapour) and
prof. A.Cogoli (Microbiology)
- University of Freiburg (West Germany)
dr. W.Littke (Protein Crystal Growth)
dr. R.Nitsche (Crystal Growth)
- Intospace (West Germany)
dr. H.Sprenger (Metallurgy)
- Technical University of Berlin
prof. G.Frohberg (Thermodynamics)
- DFVLR, Cologne (West Germany)
dr. B. Feuerbacher (Material Science)
- DFVLR MUSC (Microgravity User Support Center), Cologne
(West Germany)
prof. K. Wittmann (Material Science)
- Brunel Institute of Biotechnology (UK)
prof. H. S. Wolff (Life Science, Biotechnology)
- University of Aarhus (Denmark)
prof. O. Rasmussen (Plant Biology)

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- ZARM (Centre of Applied Space Technology and Microgravity), Bremen (West Germany)
- ACCESS (Aachen Centre for Solidification in Space), Aachen (West Germany)
dr. S.Rex, dr. P.R.Sahm (Metallurgy, Composites)
- Kodak Research Dept., (UK)
dr. J.Padday (Fluid Physics)
- CNRS, CRCCHT, Orleans (France)
dr. I.Goekalp (Combustion)
- RWTH, Aachen (West Germany)
prof. J.Richter (Thermodynamics, Physical Chemistry)
- University of Clermont Ferrand (France)
prof. R.Cadoret (Crystal Growth from Vapour)
- Technical University of Clausthal (West Germany)
prof. G.H.Frischat (Glasses)
- Royal Institute of Technology - Dept of Casting of Metals, Stockholm (Sweden)
prof. H.Fredriksson (Metallurgy)
- Laboratory of Mineralogy and Crystallography - Universities of Paris, VI and VII (France)
prof. F.Lefauchaux, prof. M.C.Robert, prof. A.Authier (Crystal Growth from Solution)
- University of Bordeaux (France)
dr. J.C.Launay (Crystal Growth from Melt)
- University of Marseille (France)
prof. B.Billia (Metallurgy)
- State Hospital of Copenhagen (Denmark)
prof. F.Bonde-Petersen (Animal Physiology)
- University of Madrid (Spain)
prof. R.Marco (Animal Physiology)
- University of Toulouse (France)
prof. H.Planel, prof. R.Tixador (Cell Biology)

In USA:

- University of Pennsylvania, Department of Biology
prof. A.Brown (Plant Biology)

